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3D Printing Provides a Precise Approach in the Treatment of Tetralogy of Fallot, Pulmonary Atresia with Major Aortopulmonary Collateral Arteries

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Abstract

Patients with tetralogy of Fallot, pulmonary atresia, and multiple aortopulmonary collateral arteries (Tet PA MAPCAs) have a wide spectrum of anatomy and disease severity. Management of these patients can be challenging and often require multiple high-risk surgical and interventional catheterization procedures. These interventions are made challenging by complex anatomy that require the proceduralist to mentally reconstruct three-dimensional anatomic relationships from two-dimensional images. Three-dimensional (3D) printing is an emerging medical technology that provides

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added benefits in the management of patients with Tet PA MAPCAs. When used in combination with current diagnostic modalities and procedures, 3D printing provides a precise approach to the management of these challenging, high-risk patients. Specifically, 3D printing enables detailed surgical and interventional planning prior to the procedure, which may improve procedural outcomes, decrease complications, and reduce procedure-related radiation dose and contrast load.

Introduction

Tetralogy of Fallot with pulmonary atresia (Tet PA) encompasses a wide spectrum of severity ranging from atresia of the pulmonary valve to complete absence of native pulmonary arteries. This range of anatomic severity may be categorized into four main groups [1]:

1. Simple atresia of the pulmonary valve or infundibulum with presence of the main pulmonary artery (MPA)
2. Absence of the MPA with continuous branch pulmonary arteries supplied by the patent ductus arteriosus (PDA)
3. Severely hypoplastic branch pulmonary arteries with presence of multiple aortopulmonary collateral arteries (MAPCAs)
4. Absence of the native branch pulmonary arteries with pulmonary blood supply entirely from aortopulmonary collaterals

Patients with tetralogy of Fallot with pulmonary atresia and MAPCAs are a heterogeneous group. Blood supply to the lungs may be from the PDA, MAPCAs, or in some instances collateral flow from coronary arteries [2], bronchial arteries, or pleural arteries [3] (Fig. 1). Often a complex combination of collateral pathways exists that are unique to each individual patient. The intracardiac anatomy is similar to that of tetralogy of Fallot with pulmonary stenosis, although the natural history for these patients is highly variable and dependent on the characteristics of the native pulmonary arteries and MAPCAs [3, 4]. Clinically, these patients may have symptoms of cyanosis or heart failure, depending upon the amount of pulmonary blood flow. Precise understanding of native pulmonary artery anatomy as well as complex and variable MAPCA anatomy is critical for optimal surgical results and clinical outcomes.

Current treatment

Outcomes for repair of Tet PA MAPCAs to a large extent depend on the size and distribution of the native pulmonary arteries. The goal of a successful repair is to provide flow to the greatest number of lung segments that resembles physiologic flow, both in terms of volume and pressure characteristics [5]. This may be accomplished via several strategies, including surgery and interventional catheterization. Optimal treatment and timing remain a matter of debate. Briefly, initial therapy may consist of one of two main strategies:

1. Reestablishment of flow to the central pulmonary arteries with a systemic-to-pulmonary artery shunt or right ventricle to pulmonary artery shunt, followed by delayed complete repair
2. Unifocalization of MAPCAs to the central pulmonary arteries in one or several stages, with simultaneous or delayed repair of intracardiac defects

Both approaches have strengths and limitations depending on the patient's anatomy [1, 3–5, 6•, 7–11]. The surgical approaches are usually performed in

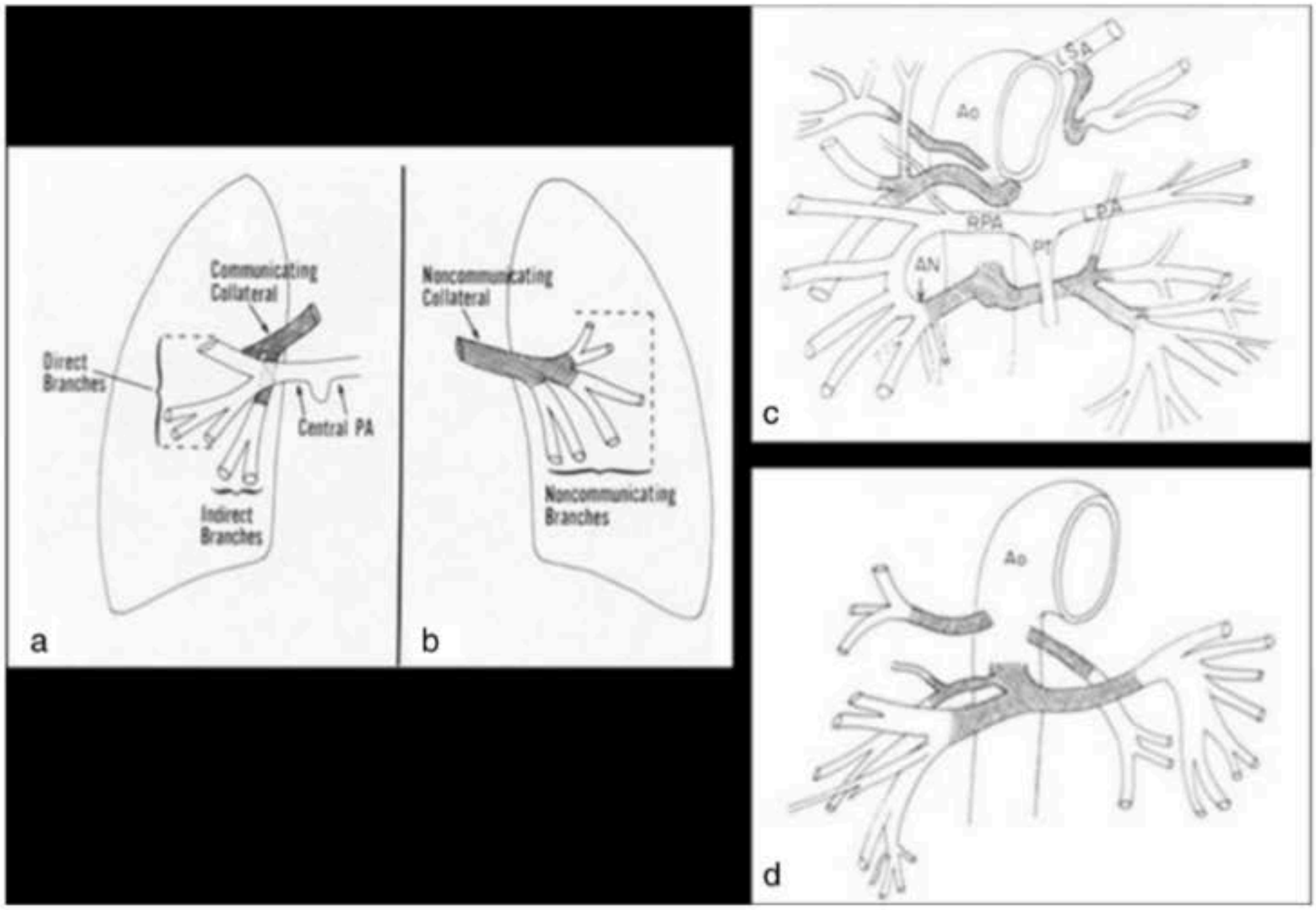

Fig. 1. Types of major aortopulmonary collaterals. **a**, **b** Schematics showing AP collaterals with direct and indirect communications with a branch of the native pulmonary artery (**a**) and APC with no communication with the native pulmonary arteries (**b**). **c**, **d** Different examples of MAPCAs, with native pulmonary arteries (**c**) and absence of central pulmonary arteries (**d**). PA, pulmonary artery; Ao, aorta; LSA, left subclavian artery; RPA, right pulmonary artery; LPA, left pulmonary artery; PT, main pulmonary trunk; AN, systemic pulmonary arterial anastomosis. Adapted with permission from [3].

concert with serial catheterization procedures to delineate MAPCA anatomy and define and eliminate dual sources of pulmonary blood flow, intervene on stenotic vessels and assess hemodynamics.

Key challenges with current treatment

Procedural planning and repair of Tet PA MAPCAs presents key challenges related to the complexity of the anatomy. This is well described by Jonas et al. when discussing the surgical planning for Tet PA MAPCAs from angiographic data:

After continuity has been achieved between the right ventricle and true pulmonary arteries…it is possible to advance a catheter from the right ventricle into the true pulmonary arteries. It is now essential to define the blood supply of each of the 20 bronchopulmonary segments of the lungs, i.e. whether

a segment is supplied by a branch of the true pulmonary arteries, by a collateral vessel, or whether there is duplicate supply. In addition an attempt should be made to define the level at which the true pulmonary arteries communicate with collateral vessels if indeed there is communication. Finally, it is important for the surgeon in particular to understand the relationship of the collateral vessels to other mediastinal structures, especially the trachea and esophagus. Some collateral vessels pass posterior to the esophagus, some pass between the trachea and esophagus and some pass anterior to the trachea and bronchi. It is even possible for a single collateral to bifurcate into two branches, one of which passes between the trachea and esophagus and the other behind the esophagus or in front of the trachea. This must be carefully studied on the lateral or anterior oblique views since a review of the AP projection alone may mislead the surgeon into believing that a simple unifocalization procedure can be achieved [1].

Figure 1 provides a schematic of Tet PA MAPCA anatomy and examples of the complex variations. While angiography and dynamic imaging from cardiac catheterization are essential to elucidating the anatomy *and* physiology of Tet PA MAPCAs, it requires a high degree of expertise to integrate two-dimensional angiographic images and mentally reconstruct the three-dimensional relationships of MAPCAs and other vital structures to strategize interventional and surgical procedures. Catheterization is also constrained by its invasive nature and need for general anesthesia, as well as contrast load and radiation exposure, which frequently limit the investigations or interventions during a single procedure.

Suggested treatment: integration of three-dimensional printing

Three-dimensional (3D) printing is an additive manufacturing technology that has been increasingly utilized in medical applications over the past two decades [12]. 3D printing produces a physical model that is a replica of the patient's own anatomy, allowing detailed visualization of complex 3D relationships. There has been increased use of 3D printing in cardiovascular applications [13], with a robust experience in structural [14•, 15] and congenital heart disease [16•, 17–19, 20•]. One of the earliest applications of cardiovascular 3D printing was for Tet PA MAPCAs, described by Ngan et al. in 2006 [21] and more recently by Ryan et al. [22]. Briefly, 3D printing requires a volumetric imaging dataset that contains the anatomy of interest. In cardiac 3D printing, datasets are usually derived from contrast-enhanced computed tomography (CT) or magnetic resonance (MR) images [14•, 16•, 20•, 23], with emerging utilization of 3D echocardiography as well [24–26]. For Tet PA MAPCAs, contrast-enhanced cardiac CT angiogram (CTA) is our preferred modality given the high spatial resolution and fast scan times. These datasets rely on isotropic voxels. CTA allows for anatomic evaluation of collateral pathways, coronary arterial anatomy, cardiac anatomy, and extracardiac structures. Limitations of cardiac CTA include radiation dose, exposure to iodinated contrast, and occasional need for sedation. Cardiac CT can be ECG-gated either retrospectively or prospectively to reduce cardiac motion artifact in order to better delineate smaller structures in the setting of high heart rates. Techniques employed both during and after the acquisition of images can be used in combination to decrease radiation dose

while still providing excellent anatomic detail. In the setting of Tet PA, ECG gating is not always necessary as delineation of larger vascular structures (main pulmonary arteries, branch pulmonary arteries, MAPCAs, and aorta) and extracardiac structures is of primary concern. Additionally, with newer generation multidetector CT scanners and high pitch acquisition techniques (e.g., dual source, flash CT), it is often possible to obtain a detailed examination without sedation and relatively low radiation exposure. These newer generation scanners provide improved spatial and temporal resolution with the ability to cover a large anatomic volume. High-pitch scan modes often allow for fast scanning of the pediatric chest, reducing both cardiac and respiratory motion artifact. In addition to detailed imaging of cardiovascular structures, CT also provides excellent evaluation of other thoracic structures including the airways, lung parenchyma, esophagus, and skeletal anatomy.

Our group has previously described the use of 3D printing in surgical planning of a staged repair in a patient with Tet PA MAPCAs [20•]. A prototypical case is shown below in order to illustrate the concept (Fig. 2). The patient is a 10-month-old male with Tet PA MAPCAs with diminutive native central pulmonary arteries. He underwent a central aortopulmonary (Mee) shunt as a neonate and a 3D model was printed for surgical planning. The 3D model was printed from a contrast-enhanced cardiac CTA.

Figure 2 and Supplemental Video 1 show a multicolor 3D printed model that shows the critical anatomy: central aortopulmonary shunt, native pulmonary arteries, MAPCAs, and relationship to key surrounding structures such as airways and pulmonary veins.

Advantages of 3D printing in Tet PA MAPCAs

3D printed models provide cardiothoracic surgeons and interventional cardiologists an accurate and holistic representation of the anatomy that is not

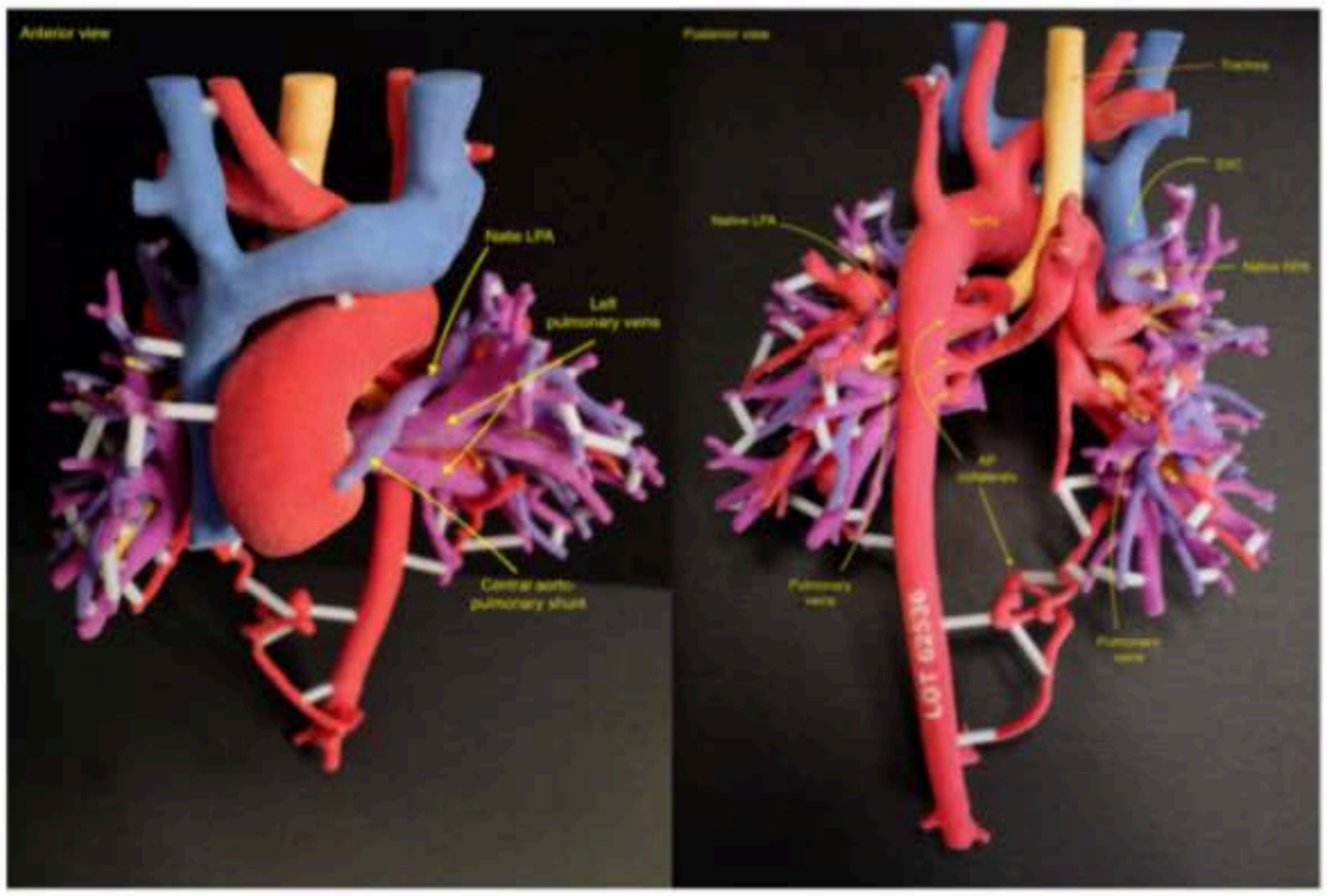

Fig. 2. 3D printed model of a 10-month-old patient with Tet PA MAPCAs, status post-central aortopulmonary shunt in infancy.

achieved with current imaging technology alone (angiography/fluoroscopy, CT). Although volume rendering, a post-processing technique, can produce "3D" objects, these images are constrained to two-dimensional representations of the viewing screen. 3D models can add significantly in the management of Tet PA MAPCAs in three distinct ways:

1. *Planning of the initial procedure*. 3D printing can show the key anatomy pertinent to decision-making with a high level of detail. Reviewing the models in combination with source CT images, the congenital cardiac team can make highly informed decisions regarding the sources of pulmonary blood flow, segments of lung supplied by native PA vs MAPCAs, and relationships to key thoracic structures [27].

2. *Integration with cardiac catheterization*. The role of cardiac catheterization in the initial assessment of patients with Tet PA MAPCAs is largely related to the identification of dual sources of pulmonary blood flow. In order to define dual source perfusion, one must be vigilant in localizing the native pulmonary arteries and all major AP collaterals. After localizing the various sources, high-quality selective angiograms must be performed in an effort to scrutinize the passage of contrast throughout the capillary phase. Having a 3D printed model prior to such cases will obviate the need for large volume power injections into the aorta because the number and location of AP collaterals is already known. Therefore, at the beginning of the case, effort can immediately be directed toward selective cannulation of the various AP collaterals. As such, this streamlined approach limits both contrast load and radiation dose. Beyond the initial assessment of Tet PA MAPCAs, 3D printed models also allow for pre-procedural assessment of complex sub-segmental branch PA stenosis in an effort to optimize contrast use and maximize interventional benefit. Without sophisticated 3D models, many modern catheterization laboratories will begin MAPCA cases with rotational angiography to visualize the entire pulmonary vascular tree. This technique requires a relatively large contrast bolus and frequently requires rapid ventricular pacing or IV administration of adenosine to optimize image quality. Furthermore, intraprocedural image processing takes time, which prolongs anesthesia exposure. Once a holistic assessment of the pulmonary vascular tree is made, then interventions can be prioritized based on stenosis severity and distribution of compromised lung segments. Balloon angioplasty and/or stenting of distal segments is frequently limited by the total contrast load, which makes serial catheterizations necessary for a number of severely affected patients. Pre-catheterization 3D modeling simply allows for complete assessment and prioritization before starting the case, which frees the interventionalist to optimize the contrast load for interventions. Finally, the potential decrease in lifetime radiation dosage and anesthesia exposure will likely benefit the patients.

3. *Surgical planning*. As discussed in the previous section, 3D printed models provide a tangible representation of complex 3D anatomic relationships. This enables the surgical team to devise a strategy prior to the surgery, including surgical approach (sternotomy vs thoracotomy), technique, cannulation, and cardiopulmonary bypass. Especially when planning a complex unifocalization procedure, this advanced preparation may save considerable time during surgery. During the surgery, models can provide a

convenient reference during dissection and identification of MAPCAs, which may be obscured by blood in the field or difficult exposure. Consequently, 3D models may contribute to lowering complications and residual lesions. More data is needed to demonstrate the impact of 3D printing on surgical outcomes, though there is some early evidence showing 3D models are effective in lowering operative time [28, 29].

Conclusion

3D printing is an emerging technology with the potential to significantly improve outcomes in patients with tetralogy of Fallot, pulmonary atresia, and multiple aortopulmonary collateral arteries. This technology enables more precise management than is possible with current standard of care. 3D printing may become incorporated into routine management in the future, though more evidence regarding the clinical impact of 3D printing is needed at this time.

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Compliance with Ethical Standards

Conflict of Interest

The authors declare that they have no conflicts of interest.

Human and Animal Rights and Informed Consent

This article does not contain any studies with human or animal subjects performed by any of the authors.

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